Pixel Pitch versus Lenses: The Effect of Modulation Transfer Function (MTF)

Scenario:

A CCD camera and a competing camera are in a shootout. All aspects of the "test" system (including lighting, power supplies, lenses, "price", etc.) remain constant, with only the cameras as variables. This setup provides a direct comparison between the performance of camera A and camera B.

Camera A has a pixel pitch of 10µm x 2048 and camera B has a pixel pitch of 14µm x 2048. The test system has been "optimized" to run camera B.

By introducing camera A, with the smaller pixel pitch (and therefore able to image more pixels), the belief is that this camera will perform better then camera B.

End result: Camera A, even with the smaller pixel pitch, maintains the same dots-per-inch (DPI) as imaged by camera B and loses the shootout. The following Application Note explains why.

General Theory:

(Please note that the following information is of a general nature and does not deal with specific formulas, specifications, etc. It is meant to provide a good base on which more theory and information can be collected.)

The main reason camera A loses the shootout can be attributed to the lens used in the system. Although there is no problem with the lens itself, it has been optimized to work with camera B. All lenses have a characteristic called Modulation Transfer Function (MTF) which is related to the "resolving ability" of the lens and affects the camera and the system.

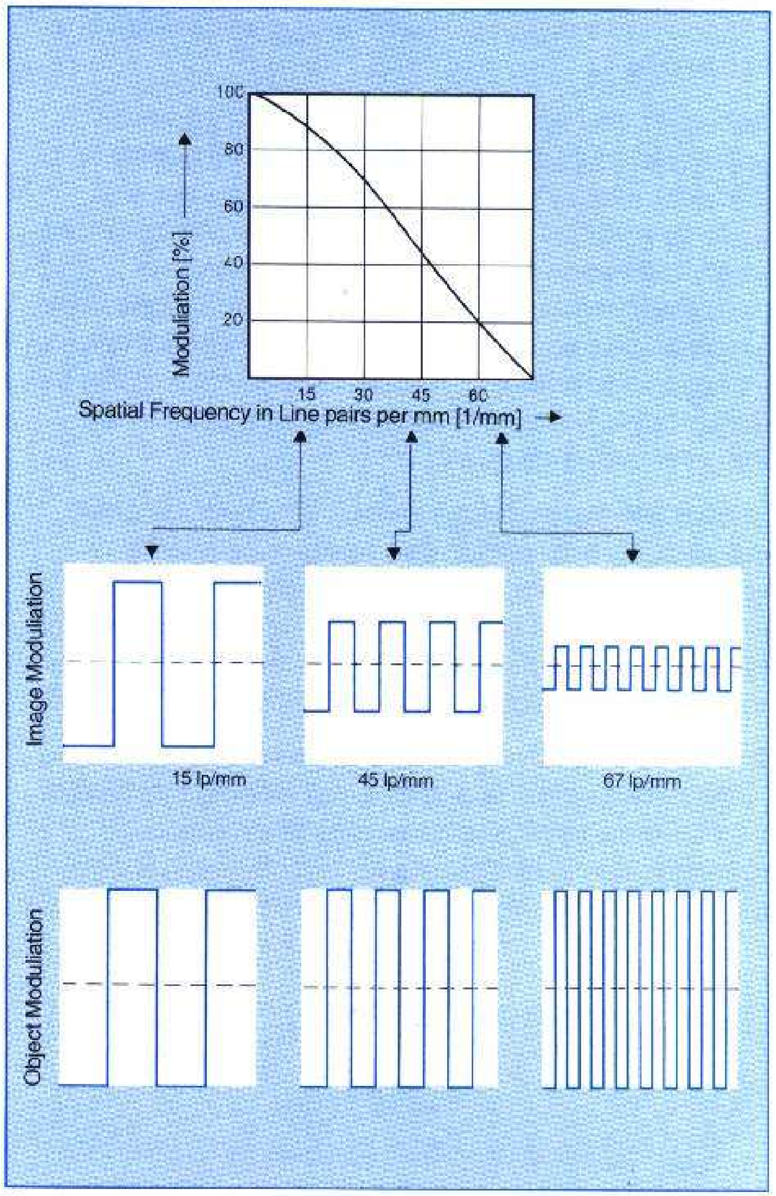
MTF – What is it and how does it relate to a CCD camera and smaller pixel pitches?

A perfect lens would fully reproduce an image from an object with absolutely no degradation. However, a perfect lens does not exist. Sharpness, contrast, illumination, spectral transmission and distortion all effect the ability of a lens to reproduce an image.

A lens can adequately reproduce an image from an object until it reaches a point where the image detail can no longer be reproduced from the object. In other words, the lens can only resolve so much detail in terms of spatial frequency. The greater the amount of detail in the object, the higher the spatial frequency of the image.

MTF is measured as a percent on a scale from 0 to 1 or 0% to 100%. 0% indicates a dark line and 100% indicates a white line. The optical industry standard for measuring MTF uses a spatial frequency unit called “line pairs per millimeter” or lp/mm.

The following graph (*Graph 1.*) indicates how increased spatial frequency (or increased detail/resolution) decreases the MTF of a lens. Therefore, the more detailed your subject the lower your MTF, resulting in a decrease in the ability to resolve that detail in the image.



Graph 1: Illustration of MTF

Graph 1.(courtesy of Schneider Optics)

Another way to look at MTF is to recognize that the finer the detail of the object going through the lens, the less able your lens will be to reproduce a good image; the image becomes less distinguishable.

The following figure (*Figure 2.*) illustrates how finer detail (higher spatial frequency) in the object experiences lower MTF and therefore is poorly reproduced in the image.

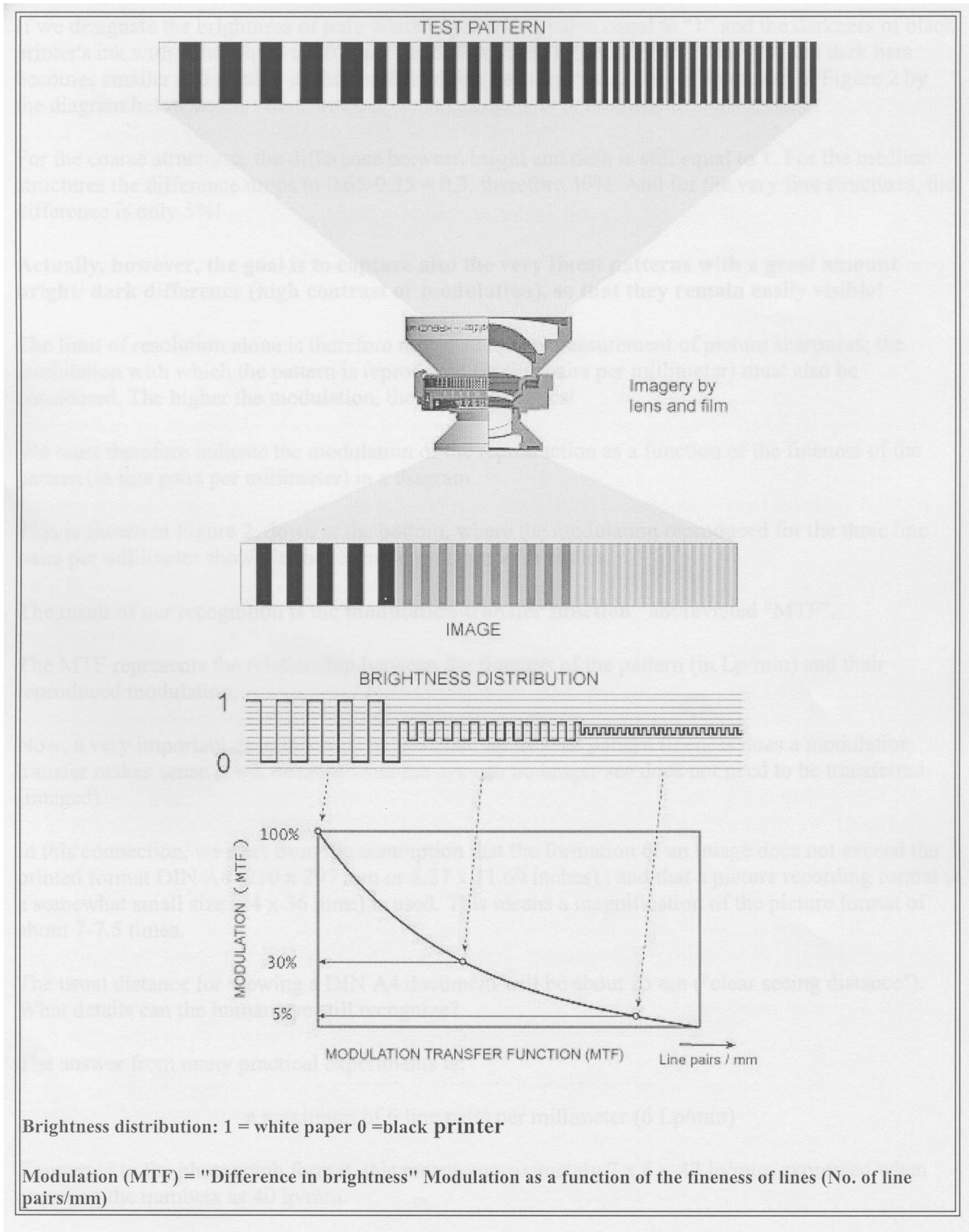
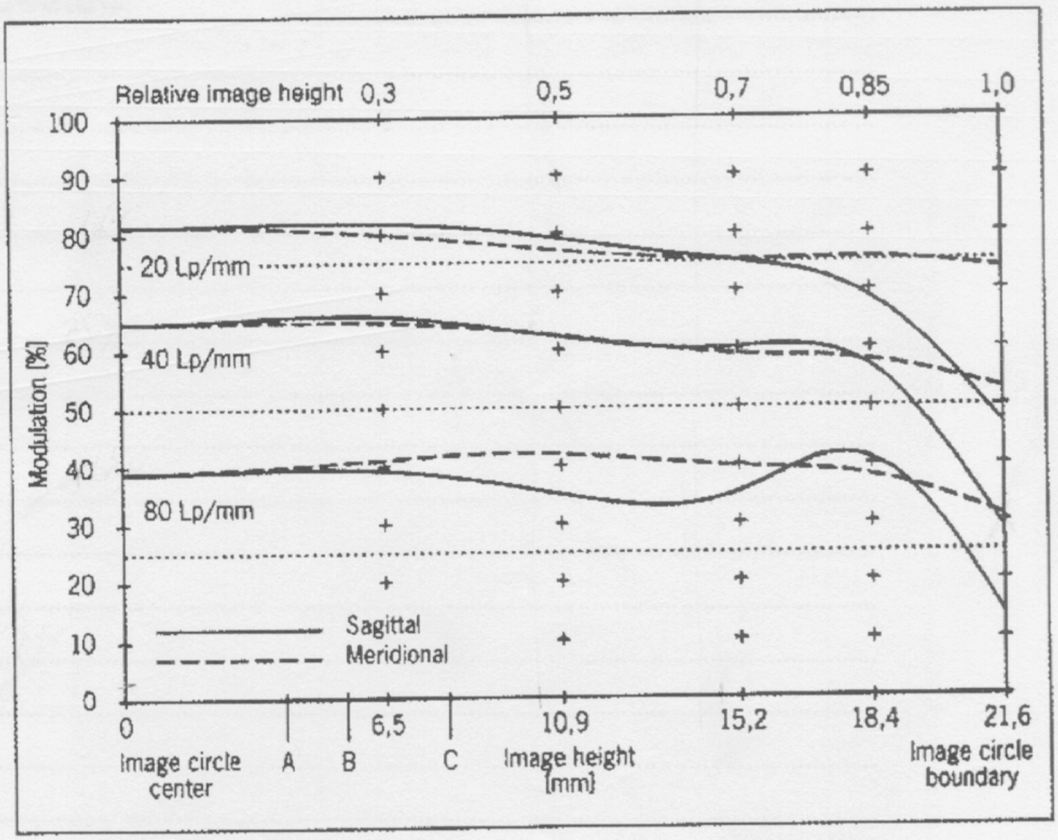


Figure 2. (courtesy of Schneider Optics)

In order to understand MTF as it applies to a specific lens, the following graphic depicts an MTF datasheet from Rodenstock. The MTF has been plotted at different resolutions (or lp/mm). Notice how as the detail increases (in lp/mm) the MTF decreases.



MTF curves of the Rodenstock Apo-Rodagon-N 50 mm f/2.8 as a taking lens for the scale of 1:10 at stop 2.8 for the spatial frequencies 20, 40 and 80 lp/mm.
A: Picture corner at 1/2" CCD surface chip (size 6.4 x 4.8 mm)
B. Picture corner at 2/3" CCD surface chip (size 8.8 x 6.6 mm)
C: Picture corner at 1" CCD surface chip (size 12.8 x 9.6 mm)

Datasheet 1. (courtesy of Rodenstock Optics)

From the Rodenstock datasheet, you can see the plots for 20, 40 and 80 lp/mm, where 20 lp/mm is the curve at the top with a high MTF and 80 lp/mm is the lowest curve with the worst MTF.

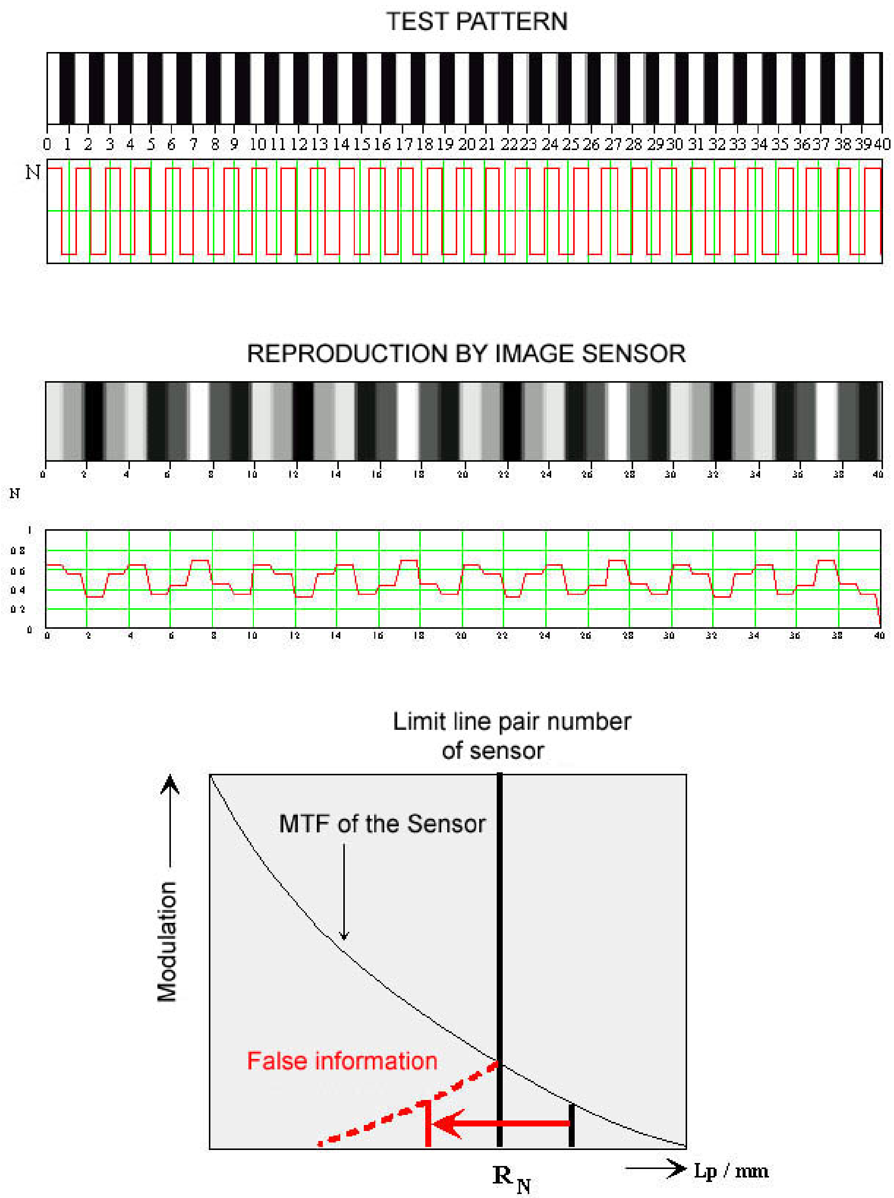


FIGURE 3. (courtesy of Schneider Optics)

Now consider the sensor's pixel pitch and the image being reproduced. The above figure indicates what happens when the object has "finer detail" then the pixel pitch. This test pattern shows approximately 7 line pairs for 10 pixels. Some sensor pixels will collect information from both dark and white lines resulting in a signal level between 0 and 1 (i.e. gray). For this sensor to work adequately there should only be 5 line pairs per 10 pixels. So once again, an increase in object detail will not necessarily be captured in the image.

Scenario Conclusion:

The above information details the relationship between lenses and MTF, but how does this relate to the pixel pitch of a sensor and camera? Returning to our original shootout scenario: the lens used in the system is the same for both camera A and B, so should it not be resolving the same quality image?

To explain this discrepancy we need to understand how the pixel pitch relates to MTF. This can be easily done through the following method:

$$R = \left(\frac{1}{2 \times P}\right)(lp/mm)$$

R = maximum line pair number, and P = pixel pitch

Camera A has a 10µm pixel that equals .010 mm. Two pixels are needed for a line pair that then equals .020 mm. Take the inverse of this and you get 50 lp/mm.

Camera B has a 14 µm pixel and that equals .014 mm. Two pixels are needed for a line pair and that then equals .028 mm. Take the inverse of this and you get 35.7lp/mm.

If camera A resolves 50 lp/mm and camera B resolves 35.7 lp/mm, then camera A will have a lower MTF.

If the same lens is used with two cameras that have different pixel pitches, then camera A with the smaller pixel, and thus experiencing a lower MTF, may not be able to resolve the same detail as camera B.

To make camera A work better in the application a different lens would be required. This new lens would have to give the same MTF performance for the 10µm pixel as the original lens was giving for the 14µm pixel.

Overall conclusions:

1. A higher MTF value (ie. 90%) results in a highly defined image from an object.
2. A lower MTF value (ie. 10%) results in a poorly defined image from an object.
3. A smaller pixel pitch results in a lowered MTF.
4. A larger pixel pitch results in better MTF.
5. The lens and pixel pitch play an important role when imaging specific detail. Careful consideration should be taken when selecting these items for your required application.

Reference Material:

1. Optics for Digital Photography. Courtesy of Schneider Optics as written by Dr. Karl Lenhardt.
2. www.schneideroptics.com WEBSITE for illustrations
3. www.rodenstockoptics.com WEBSITE for camera specifications.